Indian J. Phys. 48, 973-982 (1974)

Terrestrial solar cell power stations*

A. BHASKARARAO

Semiconductors Division, Electronics Corpn. of India Limited, Hyderabad

(*Received 6 February* 1974)

The economic and technical future of terrestrial solar cell power stations, with reference to the present state-of-the-art in solar cell fabrication technology has been discussed. The differences in optimization criteria for solar cells in outer-space and terrestrial environments are pointed out. The advantages and limitations of terrestrial solar cell power systems have been reviewed briefly. It has been shown how the installation costs of a solar cell power station are prohibitive at present (Rs. 7 lakhs/KW). Some of the promising recent developments in silicon technology that could improve the economics of solar cell power stations have been identified.

1. INTRODUCTION

At present a very large fraction of all energy comes from coal and hydro-electric power. The rest comes from oil, and natural gas. A small fraction of it comes as nuclear-power. The energy potential of nuclear fuels is well known. Besides nuclear fuels, solar radiation is another major and untapped perennial source of energy. Solar energy reaching us annually appears to be more than 30,000 times the present total energy consumption. Naturally, the possibility of directly converting the solar radiation into electrical energy is one of the most exciting technological advantures.

Photovoltaic effect (Becquerel effect) was known as early as 1839. But the power output being extremely small it remained only a scientific curiosity for more than a century till the first silicon *p-n*-junction photovoltaic cell (silicon solar cell) was prepared by Chapin, Fuller & Pearson (1954). The energy conversion efficiency of the cell was around 6%. With the advent of silicon solar cell in 1954, the dream of tapping the almost unlimited energy potential of the solar radiation has become a reality. Technologically there is no reason why solar cells cannot be used to produce large quantities of electrical power from solar radiation. However, the economic viability of the photo-voltaic solar power stations still remains to be established.

*This review article has been published as a special case due to the importance of the topic dealt with.

2. State-of-the-Art in Silicon Solar Cells

Silicon solar cell is a semiconductor device which converts light directly into electricity. It is basically a simple wide area $p-n$ junction located 0.3—1.0 micron below the active surface of a single crystal silicon silice. Due to its paramountcy as a source of electrical power in space vehicles the silicon solar cell has undergone many improvements (Pfann & Van roosbroeck 1954, Prince, 1955 Mandelkorn 1965, 1966, Smith *et al* 1963,Reynard & Andrew 1966) in their design, fabrication and technique of mounting during the decade following its first fabrication in 1954. By 1962-63 the energy conversion efficiency reached a value of 12-16%. The improvements include

(a) Use of oxygen-free aluminium doped float-zoned silicon,

(b) diffusing shallow $p-n$ junctions, (upto 0.3 microns),

(c) gridded contacts,

(d) n- on-p radiation resistant cells,

(e) silver-cerium evaporated contacts,

(f) antireflection coatings ($SiO+MgF_2$), and

(g) attaching cover glasses without addhesives.

These improvements resulted in large area cells, reduced costs, better contact strength, better radiation damage resistance, high power to weight ratio, tighter mechanical and electrical tolerances and also wider environmental capabilities. Silicon solar cells are the best amongst the direct energy conversion devices and they formed a vital component in the space programmes during the last 15 years. Some of the important characteristics of a typically good solar cell are given below :

Open-circuit voltage (V_{oc}) = 0.55V;
Short-circuit current (I_{so}) = 35-40ma/cm²
Curve-factor (CF) = 0.8;
Conversion efficiency (η) at 25°C and 140mw/cm² intensity = 12-16%;
Series resistance (R) < 1 ohm;
Peak spectral response around 5000Å.

The present state-of-the-art of fabricating silicon solar cells is well defined. Good reviews on the topic are already available in literature (Bhaskararao 1973, Iles 1972). Further discussion is not taken up here.

Other important semiconductor materials used in the fabrication of solar cells are In P, Ga, As, Cd Te, Ga P, and CdS (Smith *et al* 1963, Wolf 1961, Wysocki 1961, Loferski 1956, Rappaport 1966). There are several reasons for preferring silicon over the others (Bhaskararao 1973). Further, the technology of compound semiconductors is not as much advanced as we wish.

3. Flow Chart

The important steps involved in the installation of a solar cell power station are given in figure 1.

POLYCRYSTALLINE SILICON
↓
SILICON SINGLE CRYSTAL
↓
SOLAR CELL BLANKS
↓
DIFFUSION
↓
CONTACT APPLICATION
↓
ANTIREFLECTION COATINGS
↓
ELECTRICAL TESTS
↓
SOLAR CELL ARRAYS ← SOLAR RADIATION
↓
POWER PROCESSING UNIT
↓
CONSUMER

Fig. 1. Flow diagram for building a solar cell power station.

4. Outer-Space and Terrestrial Environments

Practical applications of solar cells may be divided into two categories, namely (i) outer-space applications and (ii) terrestrial applications. Most of the solar cells manufactured at the moment go into outer-space power systems as they are the only space-proven power systems for space missions. Only a small fraction of them go into terrestrial applications such as power sources for remote installations, reading punched cards in computers etc. In this connection, it is worthwhile to remember that the optimization criteria of solar cells in outer-space and terrestrial environments are somewhat different as shown in table 1.

5. Advantages

Photovoltaic solar power systems have several advantages over the conventional ones. They are

(a) Source of energy is almost unlimited and costs nothing.

(b) Photovoltaic energy conversion is direct, silent and free from pollution (water, thermal, and atmospheric).

(c) There are no moving parts and hence no wear and tear. Life of the system is long (more than 10 years). Frequent mainenance of the active device is not needed.

(d) They have the ability to operate unattended since refueling is not required.

(e) Power transmission problems are negligible since power can be generated at the point of consumption.

(f) The efficiency does not depend on size and hence the adaptability is high.

(g) Power generation time coincides with the periods of peak loads.

Table 1

Parameter	Outer space	Terrestrial
1. Temperature Range	$-195°C$ to $+170°C$	$-70°C$ to $+65°C$
2. Spacing between grid-fingers	Spacing between grid-fingers is to be suitably decreased to cope up with increased solar radiation.	Separation of 4mm between grid-fingers will do
3. Spectral matching through thin-film coatings	Possible	Highly complicated and costly since the cut-on and cut-off wavelengths of filters continuously vary due to changes in optical path lengh
4. High-energy particle radiation damage	High intensity of particle radiation results in serious damage of the cell as high as 30%. *N*-on-*P* cells are preferred as they exhibit better radiation resistance.	Intensity is very low and has practically negligible effect on cell conversion efficiency; either *N*-on-*P* or *P*-on-*N* cells may be used.
5. Adverse weather conditions	No such problem	Solar cell panel has to face at times adverse weather conditions (dust storm, hail storm, heavy rains, lightning) which might seriously affect the maintenance free operation.
6. Solar radiation concentration	It becomes cumbersone and impracticable	Large arm panels in conjunction with simple radiation concentrators can cut down the cost of power by a factor of 5 to 6.
7. Power to weight ratio.	Very essential in view of limited payloads of space vehicles.	High power to weight ratio is desirable but not critical.

6. Limitations

Solar cell power systems have their own limitations as well. Some of them are

(a) Energy density is not high. Solar intensity is only 140 mw/cm² outside the earth's atmosphere and much less on the earth's surface depending on the weather conditions. Vast areas of array are to be exposed to generate substantial amount of power.

(b) The source of energy is not continuous and reliable. Storage problems arise. It cannot be a substitute to conventional power. At best, it can only supplement conventional power.

(c) Generated power is D.C. and of low voltage. Power processing units are necessary before it becomes acceptable to the consumer.

(d) Infrared and ultraviolet parts of solar spectrum do not contribute to the output of the system. Conversion efficiency is still 12-16% and low compared to conventional power generation and nuclear power. economic feasibility has yet to be established.

(e) Protection of vast sensitive areas from lightning and adverse weather conditions and frequent cleaning of the surface of panels are problems.

(f) Ageing effects on the solar cell panel under the ultraviolet component of the solar radiation are to be taken into account.

7. Factors Affecting Power Output

The electrical power output from a solar cell depends upon the overall conversion efficiency of the cell, load resistance/load voltage, the equilibrium temperature of the cell, the spectral composition of the incident radiation and finally the intensity and angle of incidence of the radiation.

8. Characteristics

In the case of solar cells the following characteristics have to be measured before they are mounted on the panel.

(a) Series resistance (Prince 1955, Wysocki 1961, Wolf *et al* 1963, Handy 1967)

(b) Curve Factor, CF (Prince 1955, Loferski 1956 Cummerow1964, Wolf 1960)

(c) Conversion efficiency,

(d) Spectral response (Jordan 1960, Dale & Smith 1961, Terman 1961) and

(e) Mechanical strength of contact leads (Smith *et al* 1963, Mandelkorn 1966, Wolf 1961, Beckman *et al* 1966, Wolf 1960).

9. Silicon Versus Cadmium-Sulphide

Silicon solar cells and CdS–Cu_2S thin-film solar cells are the two most important competitors to go on to the solar cell panel. The thin-film solar cells have several points in their favour—

(a) Low cost of basic material,

(b) low cost of manufacturing process,

(c) higher power to weight ratio, and

(d) low solar-cell panel cost due to large area of an individual cell (50-100 cm^2).

However, it must be realised that silicon solar cell has better conversion efficiency, 14-16% (expected to go up to 19% by 1980) compared to Cd S–Cu_2S cell which has a maximum efficiency of only 8.3% (Rappaport *et al* 1962, Perkins 1968, Ratajczak *et al* 1968, Shirland *et al* 1968). The progress made by Cadmium-sulphide seems to be slow. Of course it must be recognised that CdS–Cu_2S thin-film solar cell has not been subjected to as much research and development as silicon solar cell. Theoretically higher conversion efficiencies are expected from CdS–Cu_2S solar cell. It is yet to be seen which of the two wins the race, although silicon solar cell is far ahead of its closest competitor for the time-being.

10. Economical Aspects

The cost of a solar cell power station depends mainly on the following factors

(a) cost of solar cell panel,

(b) life-time of the panel and other components,

(c) cost of site preparation and deployment,

(d) operation and maintenance, and

(e) cost of power processing unit.

Of all these factors, the cost of solar cell panels dictates the economics of the solar cell power system. With the existing technology, it is now possible to manufacture silicon solar cells in large quantities having efficiencies 12-16% at 25°C and 140 mw/cm^2 solar intensity. Every solar cell can be treated as a battery having an open-circuit voltage (V_{oc}) of 0.55V and short-circuit (I_{sc}) of 30-40% ma/cm^2 under optimum conditions. There are no major improvements in the performance of solar cells during the decade following 1962-63 except that the average efficiency of the cells moved closer to the highest value due to better silicon crystals and improved process techniques.

The approximate installation cost of a solar cell power station of one KW capacity is estimated here, under the assumptions mentioned below :

Solar constant = 140mw/cm^2.

Average transmission coefficient of the atmosphere = 75%

Solar cell panel is fixed.

Average efficiency of solar cell = 14%

Percentage average of the solar radiation falling on the panel compared to noon intensity due to the variation in angle on incidence from dawn to dusk = 62%

These assumptions lead to the following ratios

$$
\begin{aligned}
\text{Power/area} \quad &\simeq 10 \text{ mw/cm}^2; \\
&\simeq \text{W}/100 \text{ cm}^2, \\
&\simeq \text{KW}/10^5 \text{ cm}^2, \\
&\simeq \text{KW}/10 \text{ m}^2.
\end{aligned}
$$

The diameter of silicon single crystal is around 32 mm. The cost is somewhere between Rs. 10,000 to Rs. 15,000 per kg. One kg. of silicon may give around 1000 wafers of 12 mil thickness which is the typical thickness of solar cell blanks. Thus the cost of solar cell blank turns out to be Rs. 3-4/cm^2. It will cost at least Rs. 2-3/cm^2 to process these blanks into solar cells. Therefore

Cost of solar cell : Rs. 6/cm^2.

Cost of solar cell panel : Rs. 6 lakhs/kw.

If the cost of site, deployment, maintenance and power processing unit are included, the installation charges of a solar cell power station may go up to Rs.7 lakhs/kw. The investment seems to be certainly prohibitive. Further, at a cost of 30 paise per unit, the time required to recover the money invested in a solar cell power station works out to be more than 500 years. Thus the large scale introduction of solar cell power stations for terrestrial applications is still far away. A reduction in solar cell panel costs by a factor of 200-500 is a first step towards making solar energy compete with conventional power. No doubt, the picture presented above is very discouraging. However, some of the recent approaches to the cost reduction and improvements in the process technology of solar cells keep our hopes alive.

11. Recent Approaches

The economic and technical future of solar cell power stations depends on the intensive development effort in the following areas :

(a) ***Higher solar cell efficiency***

Solar cell efficiency has undergone only marginal improvements during the last 10 years. Use of low resistivity silicon (0.01 to 1.0 ohm-cm) having improved minority carrier lifetimes may be expected to push the solar cell efficiency up, primarily due to increase in Voc (Iles 1972, Rappaport 1966). It is suggested that low resistivity silicon combined with other modifications may lead to 19% cell efficiency in the next five years.

(b) *Silicon ribbon*

Most of the cost of a solar cell power station is accounted by the cost of solar cell blanks and processing of solar cells. The cost of solar cell panels is itself two to three orders of magnitude higher than the cost of conventional power generating system (Currin *et al* 1972). The EFG (Edge-defined Film-fed Growth) process by which multiple ribbons of silicon crystal having required thickness could be grown, is expected to bring down the cost of solar cell blanks by a factor of 100-300. This process is radically a new concept and may bring about a technological breakthrough in solar cell fabrication, and make solar cell power stations a reality.

(c) *Low cost high volume production*

There are mainly four techniques to fabricate a $p-n$ junction, namely, alloying, diffusion, epitaxial deposition and ion-implantation. Ion-implantation technique when combined with EFG process may lead to high-volume production of solar cells through almost continuous processing of solar cell blanks. It is well known that an increase in volume by a factor of 10 will bring down the prices by about 50%. However, it must be remembered that high-volume production with the present technology alone cannot bring down the cost of solar cell power stations.

(d) *Solar radiation concentrators*

Concentration of solar radiation increases the power output of a cell. Radiation densities greater than 25 W/cm^2 can be obtained, using concentrators (Beckman *et al* 1966, Ralph 1966). A concentration factor of 10 or more is found to be economical (Currin *et al* 1972). No difficulty is visualized in achieving concentration factors of about one hundred (Reynard & Andres 1966). Cheaper and lighter concentrators have to be designed.

12. Conclusion

Conventional sources of power are getting depleted at a very fast rate. Energy demands of the world are doubling up almost every ten years. Pollution problems are also becoming intense day by day. In these circumstances, solar radiation as an unlimited pollution -free source of energy is very attractive. With the advent of solar cell in 1954 conversion of solar radiation directly into electrical energy has ceased to be only of academic interest. Technologically, there is no reason why solar energy cannot be converted into electrical energy on large-scale.

But, with the existing technology the installation costs of a solar cell power station seems to be prohibitive (≈ Rs. 7 lakhs/kw) and nearly 1000 times costlier than conventional power systems. Most of this cost is accounted by solar cell blanks and solar cell fabrication processes. Solar cell power station is still far away from realisation.

Recent developments in silicon technology like the EFG process of growing silicon ribbon, using low resistivity silicon for solar cells with advantage, the possibility of using ion-implantation technique in conjunction with silicon ribbon for almost continuous processing of solar cells, and solar radiation concentrator designs to achieve high radiation densities, are very promising. With these developments terrestrial solar cell power stations may become a reality in the near future. In any case, a significant fraction of the energy consumption of the world may be coming from solar cell power stations before 2000 A.D.

References

Beckman W. A., Schoffer P., Hortman (Jr.) & Lof G. O. G. 1966 *Solar Energy* **10**, 132.

Bhaskararao A. 1973 *Proc. Indo-French Seminar on Optical Behaviour of Materials*. Thomson Press (India) Limited, Delhi, 435

Brandhorst H. W. (Jr.) 1972 *Proceeding of the 9th IEEE Photovolatic Specialists Conference*, Maryland, 37.

Chapin D. M., Fuller F. S. & Pearson G. L. 1954 *J. Appl. Phys.* **25**, 1522..

Cummerow R. L. 1954 *Phys. Rev.* **95**, 16.

Currin C. G., Ling K. S., Ralph E. L., Smith W. A. & Stirn R. J. 1972 *Proceedings of the 9th IEEE Photovolatic Specialists Conferences*, Maryland, 363.

Dale B. & Smith F. P. 1961 *J. Appl. Phys.* **32**, 1377.

Handy R. J. 1967 *Solid State Electronics* **10**, 765.

Iles P. A. 1972 *Proceedings of the 9th IEEE Photovolatic Specialists Conference*, Maryland.

Jordan A. G. & Milnes A. G. 1960 *I.R.E. Trans* ED-7, 242.

Loferski J. J. 1956 *J. Appl. Phys.* **27**, 777.

Mandelkorn J. 1965 NASA TMX-52102, Presented at the 19th Annual Power Source Conference, New Jersey

Mandelkorn J. 1966 NASA TMX-52206, Presented at the 20th Annual Power Source Conference, New Jersey.

Mandelkorn J. 1969 *Proceedings of the 6th Photovolatic Specialists Conference*, Vol. III, 125.

Perkins D. M. 1968 *Advanced Energy Conversion* **7**, 265.

Prince M. B. 1955 *J. Appl. Phys.* **26**, 534.

Ralph E. L. 1966 *Solar Energy* **10**, 67.

Ralph E. L. 1968 *IECEC Record*, 116.

Rappaport P. 1966 *Rev. Phys. Appl.* **1**, 154.

Rappaport P. & Wysocki J. J. 1962 *Technical Report*, RCA Laboratories.

Ratajczak A. F., Blake F. A. & Stahler M. R. 1968 NASA TMX-52458.

Reynard D. L. & Andrew A. 1966 *Applied Optics* **5**, 23.

Shirland F. A., Forestieri A. F. & Spakowski A. E. 1968 NASA TMX-52436.

Smith K. D., Gummel H. K., Bode J. D., Cuttriss D. B., Nielsen R. J. & Rosenzweig W. 1963 *Bell. Sys. Tech. J.* XLII, 1765.

Smits F. M., Smith K. D. & Brown W. L. 1961 *Journal Brit. IRE* **22**, 161.
Terman L. M. 1961 *Sol. State. Ele.* **2**, 1.
Wolf M. 1960 *Proc. Inst. Radio Engrs.* **48**, 1246.
Wolf M. 1961 *Solar Energy* **5**, 83.
Wolf M. & Ranschonbach H. 1963 *Advanced Energy Conversion* **3**, 455.
Wysocki J. J. 1961 *RCA Review* **22**, 67.
Wysocki J. J. 1966 *IEEE Trans.* NS-**13**, 168.